# WEAR PROPERTIES OF A SHOCK CONSOLIDATED METALLIC GLASS AND GLASS-CRYSTALLINE MIXTURES

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## ABSTRACT

Powder flakes prepared from 50 μm thick melt spun ribbons of Markomet 1064 ($Ni_{52.5}$ $Mo_{38}$ $Cr_8$ $B_{1.5}$ wt%) were shock consolidated in the unannealed and annealed condition. The unannealed flakes (microhardness 933 kg/mm$^2$) are amorphous while flakes annealed at 900°C for 2 hours have an fcc structure with a grain size of 0.3 μm and microhardness of 800 kg/mm$^2$. The shock consolidated amorphous powder compact (250 kJ/kg shock energy) shows no crystal peaks in an X-ray diffractometer scan. Compacts of annealed powder (400 to 600 kJ/kg shock energies) contain amorphous material (18-21%) which was rapidly quenched from the melt formed at interparticle regions during the consolidation process. The microhardness of the amorphous interparticle material is 1100 kg/mm$^2$. Wear properties of the compacts measured in low velocity pin on disk tests show low average dynamic friction values (∿0.03). The 60 hour cumulative wear appears to correlate with the energy of shock compaction and surface porosity of the compacts rather than the metallic glass content.

## INTRODUCTION

Metallic glasses, with high metalloid concentration and associated hardness, have been observed to show superior wear resistance when used as coatings on steel substrates [1]. Shock wave consolidation has been employed to produce bulk solids with metastable structures [2-5]. During consolidation, the shock energy is preferentially utilized in heating and melting interparticle surfaces [6,7]. The melted regions rapidly solidify and may form new metastable structures or retain the metastable structure of the starting powder. Shock consolidation is a unique form of thermal and mechanical processing and can be used to process metallic glass powders to form bulk amorphous solids [8,9], and crystalline powders of glass forming alloys to produce a solid mixture of metallic glass and microcrystalline material [6,10]. In this paper, we report some wear properties of a shock consolidated glass forming alloy powder containing varying amounts of glass and microcrystalline phases.

## SHOCK CONSOLIDATION

### Powder Characterization

The Markomet 1064 alloy ($Ni_{52.5}$ $Mo_{38}$ $Cr_8$ $B_{1.5}$ wt%) powder was prepared by ball milling melt spun amorphous ribbons (∿50 μm thick). Annealing of the powder at 900°C for 2 h produces a fully microcrystalline powder (confirmed by x-ray and electron diffraction). Optical microscope observations on polished and etched powder particles show that the amorphous phase resists attack by the Marbles reagent, while microcrystalline grains in the annealed powder are attacked and show a dark etching contrast [10].

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Powder Consolidation

Green compacts were prepared by static loading of the powder in steel containers and the compacts were consolidated by impact of propellent driven stainless steel flyer plates at velocities from 0.8 to 1.4 km/s. The consolidated powder compacts were recovered as ∿20 mm diameter discs ∿5 mm thick.

Optical photomicrographs of polished and etched sections of recovered compacts (plane of the shock) are shown in Fig. 1a,b. The dark etching regions in the compact of annealed powder in Fig. 1a are microcrystalline while the white nonetching regions are metallic glass (as confirmed by TEM [10]). The compact of amorphous powder, Fig. 1b shows etching at amorphous particle boundaries which did not melt sufficiently to dissolve surface contaminants. The amorphous powder compact shows no crystalline peaks in an X-ray diffractometer scan. The shock energy, glass content, and microhardness of the particles and interparticle amorphous regions are given in Table I for the four compacts used in the wear tests.

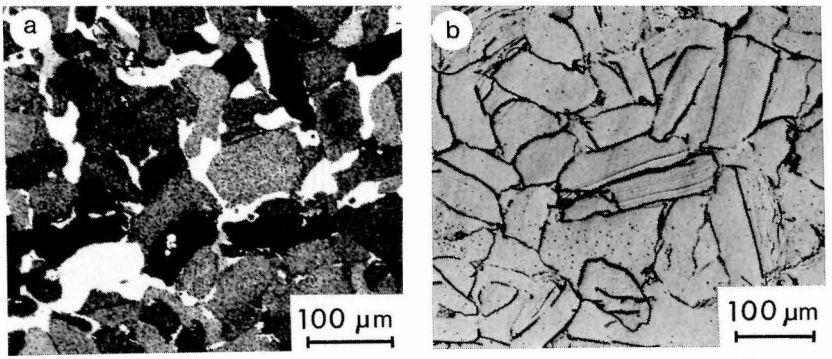


Fig. 1. Optical photomicrographs of sections (shock plane) of compacts of (a) microcrystalline powder (shot #816), and (b) amorphous powder (shot #817).

The volume fraction of metallic glass formed upon compaction was determined by measurement of the areal fraction of the nonetching glass phase in optical micrographs, and ranged from 0.18 to 0.21 with increasing shock energy. The microhardness of the glass phase formed at microcrystalline particle boundaries is greater than the hardness of the melt spun glass and the hardness of the microcrystalline particle interiors. Interparticle regions of the amorphous powder compact also exhibit a higher hardness than that in the interior of the amorphous particles.

TABLE I - CONSOLIDATION EXPERIMENTS AND RESULTS

| Shot# | Shock Energy(kJ/kg) | Glass Fraction | Microhardness(DPH,kg/mm$^2$) Particle | Interparticle |
|---|---|---|---|---|
| 813(μx+a) | 592 | 0.21 | 792 ± 134 | 1095 ± 87 |
| 815(μx+a) | 467 | 0.19 | 782 ± 99 | 1060 ± 153 |
| 816(μx+a) | 419 | 0.18 | 801 ± 205 | 1146 ± 98 |
| 817(a) | ∿250 | 1.0 | 933 ± 131 | 1144 ± 75 |

μx = microcrystalline, a = amorphous

WEAR TESTS

A low velocity friction apparatus (LVFA) [11,12], employing a three pin on disc configuration was used to obtain boundary friction test conditions which produce adhesive wear. Test samples were made from ∿3 mm discs (0.5 mm thick) of the compacts bonded to 3 mm pins. The discs were ground to match the 3 mm diameter pins with a 45° chamfer and the flat ends of the discs were mechanically polished, finishing with 5 μm diamond grit. The pins were run at 0.3 m/s on a circular track (17.5 mm diameter) on the mechanically polished surface of a disc (∿40 mm thick 52100 steel, microhardness 900 kg/mm$^2$) for a 17 h break-in period at ambient temperature prior to making measurements of friction and wear. The disc was lubricated with an automotive transmission fluid. Friction and wear values at 0.4 m/s and the highest temperature and thrust load used in the tests (149°C and 19.3 MPa pressure) are given in Table II. Wear volume was determined from optical microscope measurements of the chamfer diameter of the pins after 60 h of running. Values determined using an AISI 1095 steel pin base-line sample (microhardness 700 kg/mm$^2$) are also given in Table II.

TABLE II - LOW VELOCITY FRICTION APPARATUS RESULTS (149°C, 19.3 MPa)

| Sample # | Surface Porosity Ranking | Coefficient of Friction $\mu_{static}$ | $\mu_{dynamic}$ | $\mu_{ave\ dyn.}$ | Cumulative Pin Wear after 60 hrs. (mm$^3$) |
|---|---|---|---|---|---|
| 813 | L-M | 0.105 | 0.064 | 0.02 | 0.10 |
| 815 | M-H | 0.111 | 0.074 | 0.03 | 1.03 |
| 816 | M | 0.092 | 0.078 | 0.02 | 0.13 |
| 817 | H | 0.085 | 0.082 | 0.05 | 2.31 |
| 1095 Steel | L | 0.113 | 0.087 | 0.10 | 0.08 |

Microscopic examination of the polished surfaces of the compacts revealed some porosity due to particle pull-out. This surface porosity was observed to decrease for compacts consolidated with increasing shock energy.

Initial static and dynamic coefficient of friction values are given in Table II. There is insignificant variation in the measurements for the static friction data. The dynamic sliding friction increased with increasing load and temperature, and decreased as the sliding speed was increased. This behavior is typical for boundary friction conditions. Under the most severe test conditions (149°C, 19.3 MPa) the dynamic coefficient of friction (after the final 17 h break-in) values tend to increase with increasing porosity. Highest dynamic friction coefficient resulted with the base-line 1095 steel sample because of its greater surface roughness. The average dynamic coefficient of friction values, on the other hand are the average of the values obtained after break-in at 5 min, 1 h, and 17 h, and follow the trend for the dynamic values.

The pin volume loss in the wear tests correlates with the energy of shock compaction and surface porosity, and not with the volume fraction of metallic glass in the samples. Wear of samples #813 and #816, consolidated at high energies, was less than that of #815 and #817. Samples of shot #817 (all glass) and #815(19% glass) showed maximum wear which is attributed to particle pull-out. The increase in dynamic friction during the break-in cycle also indicates particle pull-out. In samples #813 and #816, the pin wear is equal to that of the base-line 1095 steel sample, within the limits of experimental uncertainty.

In contrast to the pin on disc test, preliminary wear test results on an all glass Markomet 1064 alloy compact in the block on disc test (at high contact pressures) indicates significantly lower wear rates than on hardened

steel base-line samples. The results of the block on disc tests will be reported elsewhere.

## CONCLUSIONS

1. Shock consolidation of amorphous powder flakes of Markomet 1064 alloy with a 250 kJ/kg shock energy produces a fully amorphous compact with microhardness ranging from 933 to 1100 kg/mm$^2$. The interparticle regions of the compact exhibit the highest hardness.
2. The shock consolidation of annealed Markomet 1064 powder produces compacts with metallic glass at microcrystalline particle interfaces. The volume fraction of metallic glass increases with increasing shock energy up to 600 kJ/kg, and the microhardness of the metallic glass and microcrystalline particles is $\sim$1100 and $\sim$800 kg/mm$^2$, respectively.
3. A porosity is observed on mechanically polished surfaces of the shock consolidated compacts which is attributed to particle pull-out. The porosity decreases with increasing shock energy.
4. Low velocity wear tests (0.4 m/s) show a dynamic coefficient of friction and a 60 h cumulative wear which correlates with the energy of shock compaction rather than the metallic glass content of the compact.
5. The compact with 21% metallic glass between microcrystalline particles (consolidated with the maximum shock energy) exhibited the lowest dynamic friction, and wear comparable to that of the hardened AISI 1095 steel base-line sample.

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